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SUMMARY

Mechanical properties are presented of the aluminum-poly[ethylene terephthalate]-aluminum laminate which is used to fabricate the Echo II passive communications satellite, and of the aluminum foil and poly[ethylene terephthalate] film which constitute the laminate. Tensile strength, Young's modulus, and elongation of 1/2-inch-wide samples were obtained for strain rates from 0.02 inch per inch per minute to 4 inches per inch per minute. Tensile stress relaxation of the laminate was determined for times up to 1,000 minutes. The flexural stiffnesses of the laminate, the aluminum foil, and the poly[ethylene terephthalate] film was measured by the heavy elastica method. The effects of fabrication and handling loads on the tensile strength, Young's modulus, elongation, and flexural stiffness of the laminate were examined.

INTRODUCTION

The successful application of the passive communication satellite, Echo I, has been amply demonstrated. The Echo I is a 100-foot-diameter balloon made of 1/2-mil aluminized poly[ethylene terephthalate] film which has been in orbit since August 1960. During that time the balloon has undergone severe distortion from its original shape. (See ref. 1.) The diameter may have decreased somewhat and what appear to be large flat areas have developed on the surface. As a result, the reflected signal has deteriorated considerably when compared with the reflected signal during the early life of the satellite.

As a subsequent experiment to Echo I, a larger (135-foot-diameter) sphere, the Echo II was designed primarily as a structural experiment. The purpose of the Echo II is to demonstrate the feasibility of erecting and rigidizing a large structure in orbit. In order to accomplish this purpose, the satellite must be light enough to be orbited at altitudes on the order of 650 to 1,000 miles by the existing boosters. In addition, the material must have sufficient strength to resist the handling and inflation loads which will be imposed upon it. The material must be very flexible so that the balloon can be compactly folded into a protective magnesium canister for transport through the atmosphere. Once in space the canister is separated from the booster, opened, and the balloon inflated with a sublimating compound; therefore, the material must be flexible as well as light and strong.

For communications purposes, it is desirable to maintain the spherical shape of the balloon against the deforming loads of solar pressure and atmospheric drag even after most of the inflation material has leaked out to space. Although the deforming loads are small (solar pressure is 1.3×10^{-9} psi, atmospheric drag is 7.2×10^{-12} psi, see ref. 2), such loads act on the balloon while it is in orbit. Most of the inflating gas will dissipate to space after a few weeks. Therefore, in order to maintain its sphericity, it is necessary that the balloon skin have resistance to buckling.

The Echo II satellite is fabricated of three-layer, aluminum-poly[ethylene terephthalate]-aluminum laminate. This paper presents the tensile strength, Young's modulus, and elongation of the laminate under tensile load. The flexural stiffness of the laminate is reported, and the effects of fabrication and handling loads on the mechanical properties are examined.

DESCRIPTION OF MATERIAL

The Echo II laminate is a three-layer, metal-plastic composite as shown in figure 1. The middle layer is 0.00035-inch-thick poly[ethylene terephthalate] film (designated PET film herein) and the outer layers are 0.00018-inch-thick 1080 aluminum foil. The layers are held together by a standard polyester cement which has been modified for this use. The total thickness of the laminate is approximately 0.0008 inch and it weighs 0.0082 pound per square foot. The biaxially oriented PET film used in the Echo II laminate is the type C or capacitor grade film. (See ref. 3.)

The 0.00018-inch-thick 1080 aluminum foil is rolled in 54-inch-wide rolls and was produced especially for use in the Echo II balloon; these rolls represent a considerable production achievement in the pack rolling of thin foil. Although the nominal thickness of the foil is 0.00018 inch, measurements made with an electrically driven micrometer indicated an average thickness of 0.0002 inch. The thickness inferred by weighing a given area of the foil of known density was 0.00019 inch. The stress calculations presented in this paper for the aluminum foil assume a thickness of 0.0002 inch. This figure gives the most conservative values of stress of the three thicknesses described.

A natural result of pack rolling aluminum in such thin gages (0.001 inch or less) is that the foil contains numerous holes, indentations, and rolling marks which undoubtedly have an effect on the mechanical properties of the foil and the laminate. Figure 2(a) is an enlarged view of the surface of the aluminum foil and figure 2(b) is a comparable view after lamination. What appear to be holes in the direct lighted view (fig. 2(a)) are actually indentations as shown by the view of the same area under oblique light. Therefore, contact negatives were made of 432 square inches of the foil in order to obtain an estimate of the density of the holes. The negatives were made on film with an ASA speed of 600 and were exposed for 5 minutes. Careful examination of the negatives indicated an average of about 20 holes per square inch. No estimate of the size of the holes was attempted, but the holes in thicker foil (0.0004 inch) range from 10^{-7} square inch to 3×10^{-5} square inch. (See ref. 4.)

Figure 2(b) shows the surface of the aluminum foil after lamination. The rolling marks and indentations of the unlaminated foil are replaced by what appear to be fine creases or accordion-like folds. Rolling marks in the laminate are visible under the oblique light.

DESCRIPTION OF TESTS

The mechanical properties of the Echo II laminate were obtained by means of three tests: the tensile stress-strain test, the tensile stress relaxation test, and the flexural stiffness test.

Stress-Strain Test

Stress-strain tests of the type discussed in reference 5 were conducted on the laminate. The load is applied to the test specimen by movement of the cross head of the testing machine at a constant rate of travel. The cross-head rates were 0.1, 0.2, 0.5, 1, 2, 5, 10, and 20 inches per minute. Although the deformation rates are equal for the aluminum foil and the PET film in a given test, the loading rates are not identical for the two materials. Within the elastic range, the loading rate for each material in the laminate is proportional to the value of Young's modulus. The test specimen was 1/2 inch wide and had parallel sides. The testing machine was set with 5 inches between the grips so that the strain rate is one-fifth the cross-head rate. The testing machine strip chart and the cross head are driven independently by synchronous motors. The load on the specimen was measured by a 50-pound-capacity load cell. An area compensator converted the load value directly to average stress in pounds per square inch. The testing-machine chart therefore yields stress-deformation curves. The average strain was obtained by dividing the deformed length of the test specimen by the original length between the grips, which was 5 inches in this case. The values of elongation refer to the values of strain at break for the aluminum foil and the PET film, and the strain at which the aluminum fails in the laminate.

Validity of strain measurements.- In order to determine whether the stress-deformation curve was representative of the stress-strain behavior of the laminate, a series of tests was conducted in which the strain was measured simultaneously by optical means and by the testing-machine chart. Two ink marks were placed on one side of the sample approximately 1 inch apart. A 70-millimeter camera operating at 30 frames a minute was used to photograph the separation of the ink marks as the tensile specimen was loaded to failure at a strain rate of 0.04 inch per inch per minute. Each opening of the shutter sent a signal to the pen on the testing-machine chart so that the strain obtained with the camera could be matched to the appropriate stress. A 6-inch scale, with least divisions of 1/64 inch provided a measure of the movement of the marks. (See fig. 3(a).) The exposed film was processed and then read on a film reader where the distance between the ink marks was measured. The camera-film reader system could detect a deformation of 0.002 inch.

Because of the low framing rate of 30 frames per minute, there was an insufficient number of photographs at the low stresses to determine Young's modulus accurately. Therefore, further tests were conducted at higher framing rates in which the test specimen was loaded to a stress of 4,000 psi. The strain was measured with a 70-millimeter camera operating at 20 frames per second, which was fitted with a lens extension and focused on the test specimen so that the 1-inch length between the ink marks occupied almost the entire field of view. The camera and the chart were started simultaneously. A 1-inch scale, with least divisions of 0.01 inch, provided a measure of the movement on the ink marks. (See fig. 3(b).) The distance between the ink marks was determined on a film reader. The camera-film reader system could detect a deformation of 0.001 inch. It was necessary, because of the limited field of view, to photograph the scale independently; therefore the scale and the test specimen do not appear on the same frame and two frames are shown in figure 3(b).

Effect of prestressing.- Some of the test specimens of the laminate appeared to be wrinkled in such a way that the specimens deformed readily at low loads. The modulus determined by such a test was lower than the modulus obtained with specimens which were not wrinkled. The wrinkles could be removed by loading the specimen to some low stress before loading it to failure. To determine whether such prestressing would affect the properties of the laminate, five stress-strain tests were conducted in which the test specimen was loaded to stresses ranging from 1,200 psi to 8,000 psi. The specimens were loaded four or five times at a strain rate of 0.04 inch per inch per minute, and then loaded to failure at the same rate.

Stress Relaxation Test

Tensile stress relaxation tests were also conducted. (See ref. 5.) The test specimen was deformed at a strain rate of 0.04 inch per inch per minute to a predetermined stress level. The cross head was stopped so that the strain associated with the predetermined stress was maintained for times up to 1,000 minutes. During this time a continuous reading was made of the stress. The test specimen was surrounded by a windshield inasmuch as the aluminum is highly sensitive to small temperature fluctuations and caused small and highly erratic changes in the stress. After the completion of the stress relaxation test the test specimen was released, replaced in the testing machine, and loaded to failure at a strain rate of 0.04 inch per inch per minute. The stress-strain test, following the stress relaxation test, provided a means of determining the effect of prolonged stress on the strength, modulus, and elongation of the laminate.

Flexural Stiffness Test

The flexural stiffness of the laminate was measured by the heavy elastica method. The derivation of the equations for use in the stiffness test is presented in reference 6 and summarized in reference 7. A detailed test procedure is given in reference 8.

In the flexural stiffness test a strip of material 1/2 inch wide was cantilevered from a flat, horizontal surface and allowed to deflect under its own weight. (See fig. 4(a).) A small weight was used to insure that there was no angular rotation at the root of the cantilever. Measurements were made of the length of overhang l and the angle of deflection θ of the free end below the horizontal. The flexural rigidity EI is equal to the product of w (the weight of the strip per unit length) and c^3 where c is a function of l and θ. The relationship between θ, c, and l is shown in figure 4(b).

Figure 4(c) shows the stiffness tester which employs the heavy elastica method. Strips of three materials, of equal width and length, but of different stiffness, are shown on the tester in order to emphasize the difference in bending resistance. The materials are the Echo I skin, the Echo II laminate, and the four-layer Explorer IX laminate. (See ref. 9.) In the actual stiffness test only one strip was tested and a clear plastic cover was placed over the tester to prevent air currents from influencing the test results. To determine the effect of applied and released stress on the stiffness of the laminate, test specimens were deformed at a strain rate of 0.04 inch per inch per minute to stresses up to 10,000 psi. The stress was immediately released, the specimen was removed from the testing machine, and the stiffness was measured as described above.

RESULTS AND DISCUSSION

The results of the stress-strain tests, the stress relaxation tests, and the flexural stiffness tests are given in tables I to IX and are illustrated in figures 5 to 12.

Stress-Strain Tests

The stress-strain behavior of the laminate is of fundamental importance to its utilization. The results of the stress-strain tests of the Echo II laminate, the PET film, and the aluminum foil are listed in tables I to IV and are illustrated in figures 5 to 7.

Validity of strain measurements.- The laminate was much too thin (0.008 inch) to receive conventional strain instrumentation such as wire-resistance strain gages, electromechanical or opticomechanical extensometers. In the stress-strain tests the increase in the distance between the grips, divided by the original distance, was taken as the unit strain of the test specimen. It was necessary to determine whether this method truly represented the stress-strain behavior of the laminate. Therefore, optical strain measurements were made and the curves so obtained were compared with the curve generated by the testing-machine chart. (See fig. 5(a).)

It can be seen in figure 5(a) that the curve obtained with the testing-machine chart and the data obtained by the optical method are very similar. The scatter in the optical data is to be expected inasmuch as the strain for the curve was determined at discrete times rather than continuously, as in the case of the chart curve. In addition, the chart curve represents average strain over a 5-inch test specimen length whereas the optical data show the strain occurring in a particular 1-inch distance. There are few data points at the low stresses because the deformation rate and the picture rate are constant with time. However, the load increases rapidly at the beginning of the test and large changes in load take place in the time interval between successive pictures. Therefore, it was necessary to examine the lower portion of the curve in greater detail.

The results of the tests which were conducted to establish the lower part of the stress-strain curves are shown in figure 5(b). Inasmuch as the total strain expected during the test is of the same order as the resolution of the camera-film reader system (0.001 inch), it is unlikely that any movement of the laminate would be detected. Therefore, the considerable movement observed by the camera indicates that small areas of the laminate may move erratically. It would be virtually impossible, then, to obtain from the optical method (even one with higher resolution) the straight line which was generated by the testing-machine chart.

The curves discussed above indicate that the testing-machine chart gives a good indication of overall stress-strain behavior of the laminate but obviously cannot be expected to indicate small transient changes in load or strain. The camera observes the surface strain over a small distance, but the testing-machine chart records the average deformation over the entire length of the test specimen. Therefore the load-deformation curves generated on the chart are taken to be representative of the overall stress-strain behavior of the laminate, the aluminum foil, and the plastic film.

Effect of prestressing.- Figure 6 shows five stress-strain curves of the laminate in which the test specimen was prestressed before it was pulled to failure as indicated in the figure. The curves show a slight change in the shape of the stress-strain curve and an increase in Young's modulus with prestress. There are three possible reasons for the increase: (1) The prestressing removes the small creases and wrinkles from the aluminum foil; (2) it cold works the aluminum foil; and (3) the prestressing orients the PET film to a limited degree. The Young's modulus for the prestressed laminate falls between the values for the unstressed laminate (3.33×10^6 psi) and the calculated modulus (5.31×10^6 psi). A reasonable compromise, then, would be a value of 4×10^6 psi for Young's modulus of the laminate.

The results of the stress-strain tests of the Echo II laminate, the PET film, and the aluminum foil are listed in tables I to III and are illustrated in figure 7 by the solid curves. The dashed curves are explained later. The strain rates, which are shown by logarithmic scales in figure 7, varied from 0.02 to 4 inches per inch per minute.

Tensile strength.- Figure 7(a) shows the effect of testing speed on the tensile strength of the Echo II laminate, the PET film, and the aluminum foil. The tensile strength of the aluminum foil varies from about 7,500 psi to 8,500 psi but remains relatively constant over the range of testing speeds. The tensile strength of the PET film, however, increases somewhat from about 23,000 psi (one test as low as 20,000 psi) at the low testing speed to about 27,500 psi at the highest. The tensile strength of the Echo II laminate increases with testing speed from about 13,000 psi to 15,000 psi.

Elongation.- The elongation at failure of the Echo II laminate, the PET film, and the aluminum foil are shown in figure 7(b) where three ordinates are used in order to accommodate the wide spread of the elongation values. A value of about 1 percent would be representative of the elongation of the aluminum foil, and although it varies widely, the elongation of the PET film may be taken as about 100 percent. The spread in the values of the elongation for the PET film illustrates the large effect that local defects and irregularities within the film have on the mechanical properties. In the laminate, however, the PET film and the aluminum foil undergo the same amount of deformation and the elongation of the Echo II laminate, when the aluminum foil breaks, varies from 5 to 13 percent.

Young's modulus.- The Young's modulus of the Echo II laminate, the PET film, and the aluminum foil was determined at a strain rate of 0.04 inch per inch per minute. The laminate was not prestressed as described previously and the modulus was 3.33×10^6 psi. The modulus of the PET film was 0.69×10^6 psi, a value which is higher than the value of 0.55×10^6 psi reported by the manufacturer for 0.001-inch-thick film. (See ref. 3.) The higher modulus of the thinner film is thought to be a result of the additional stretching which is required to produce the thin film.

The modulus of the aluminum foil as determined by the stress-strain tests was 4.92×10^6 psi. Such a value seemed to be unreasonably low when compared with the modulus of bulk aluminum of 10×10^6 psi. A large part of the difficulty resulted from the poor alinement and seating of the extremely thin foil in the testing-machine grips. It was necessary, therefore, to stress the aluminum foil several times to a stress slightly above the yield stress before the modulus could be determined. The cycling was continued until the foil failed, usually at strains of 1 to 2 percent. The average Young's modulus of the aluminum foil determined by cycling was 7.90×10^6 psi. The highest value obtained from cycles between 1,000 psi and 6,000 psi was 9.26×10^6 psi. The lower value of 7.90×10^6 psi is representative of the apparent modulus of the aluminum foil and is lower than that for bulk aluminum, probably because of the uncertainty regarding the cross-sectional area.

The aluminum had a higher elongation in the laminate than it did as a foil, and it appeared that the adhesive used in the laminate may have influenced the tensile properties of the foil. Therefore, two sheets of the foil were cemented together with an adhesive identical to that used for the three-ply laminate to form a two-ply aluminum laminate. Tensile tests were performed on the two-ply foil laminate at strain rates of 0.04, 0.4, and 4 inches per inch per minute. The results of the tests are given in table IV and are shown by the dashed curves in figure 7. The tensile strength and elongation of the two-ply aluminum-foil laminate are higher than the single foil but not as high as those for the Echo II laminate. The apparent Young's modulus of the two-ply aluminum laminate was 6.30×10^6 psi. This value was obtained by means of the stress-strain test without stress cycling. It appears, therefore, that the holes and indentations in the aluminum foil tend to lower the tensile strength, Young's modulus, and elongation of the foil from the bulk aluminum values, but that the adhesive and the process by which it is applied prevent the defects from having a full effect.

It was pointed out in "Description of Tests" that the loading rate for the materials in the Echo II laminate are not equal. Therefore, it is invalid to assume that the laminate curves in figure 7 are simply an addition or interpolation of the curves for the PET film and the aluminum foil. It can be seen in figure 7, however, that the strength and elongation curves of the laminate and the film have similar slopes. The similarity suggests that the behavior of the PET film strongly influences the behavior of the Echo II laminate with regard to strength and elongation. The Young's modulus of the aluminum foil, however, governs the modulus of the laminate.

Stress Relaxation Tests

The results of the tensile stress relaxation tests are given in table V and are illustrated in figure 8 where the stress is plotted against the logarithm of the time in minutes. Tests were conducted with initial laminate stresses in a lower range of 1,000 to 5,000 psi, and stresses in a higher range of 6,000 to 10,000 psi. At all stress levels the stress decreases linearly with the logarithm of time. If the times are extended as in figure 8, the curves appear to indicate two distinct points of intersection. The curves for the initial stress in the lower range are shown to intersect at a stress of about 100 psi and a logarithm of time of 17.7 while the curves for the higher range stresses intersect at a stress of 1,300 psi and a logarithm of time 14.8. The two points of intersection may reflect the load which is carried by the aluminum foil and the PET film. At the lower stress levels the aluminum carries most of the load so the stress relaxation curves of the laminate should be virtually those of the aluminum. At the higher laminate stresses, both the aluminum and the PET film undergo stress relaxation and the laminate curves are more truly representative of the behavior of the composite material.

The stress relaxation test demonstrates how the laminate will react to long-time fixed deformation. The Echo II balloon will be able to deform and shrink and thus will not be subject to fixed deformation. However, the information obtained from the stress relaxation test is useful for other applications of the laminate where it will be under fixed deformation, such as ribbed solar collectors.

Subsequent to each stress relaxation test, the specimen was loaded to failure at a strain rate of 0.04 inch per inch per minute. Figure 9 shows the Young's modulus obtained from the test as a function of the stress which was applied in the stress relaxation test. In addition, the modulus values from the stress-strain tests in which the laminate was prestressed are included. The curve shows that a prestress on the laminate can first decrease, then increase, and again decrease the Young's modulus obtained from a stress-strain test of the laminate. It appears also that the change is not time dependent but stress dependent, and that long-time deformation does not have any more effect on the modulus than short-time deformation does. The highest modulus was obtained with a laminate prestress of 6,000 psi.

Flexural Stiffness Tests

The results of the stiffness tests are given in tables VI and VII and are shown in figure 10. Tables VI and VII list the angle of deflection and the calculated stiffness for each test specimen. The average flexural stiffness of 70 tests of the Echo II laminate is 2.92×10^{-2} lb-in.^{2}, of 18 tests of the PET film is 1.15×10^{-6} lb-in.^{2}, and of 30 tests of the aluminum foil is 4.75×10^{-6} lb-in.^{2}. (See table VI.)

Table VII and figure 10 show the effect of previously applied stress on the flexural stiffness of the Echo II laminate. Such stress may arise from fabrication, handling, deployment, and inflation loads. The stress is applied prior to the stiffness test so that the measured stiffness reflects the effect of any modulus change or mechanical damage which has been experienced by the laminate during loading. Loading the laminate to fairly low stress levels increases the stiffness slightly to a maximum which occurs at a prestress of 4,000 psi. (See fig. 10.) For prestress above 4,000 psi, however, the stiffness of the laminate falls off rapidly until, for a prestress of 10,000 psi, the stiffness is one-third that of the unstressed laminate. It appears then that the loading of the laminate tends to make the laminate stiffer up to a point, but beyond that point, stiffness decreases. Therefore, internal pressure in the balloon which results in skin stress is beneficial from the standpoint of stiffness as long as the laminate stress does not exceed 4,000 psi.

The Effect of Fabrication and Handling Loads

The data discussed previously have been obtained from material which had not been used for any purpose except testing. There are, however, certain handling loads to which the laminate is subjected in normal use. For example, the laminate receives an amorphous phosphate coating for the purpose of thermal control of the satellite. (See ref. 10.) In addition, the laminate receives a certain amount of wear during fabrication and folding for placing into the canister.

<u>Stress-strain properties</u>.- Tensile tests were conducted on three different samples of the Echo II laminate which represented different degrees of handling. The first group of samples was taken from the unfabricated laminate which had been treated with an amorphous phosphate coating. (See ref. 10.) The second group had been fabricated into a full-scale backup satellite folded into a canister and inflated in a vacuum chamber. The third group of test specimens was taken from a 30-inch test balloon which had been inflated several times in a vacuum chamber. Both the skin and the seams from the 30-inch balloon were tested. The results of the tests at 0.04, 0.4, and 4 inch per inch per minute

are listed in table VIII and are shown in figure 11. Modulus tests were conducted at a strain rate of 0.04 inch per inch per minute. Included in figure 11 are data from table I on the tensile strength and elongation of Echo II laminate which has not been subjected to handling loads.

In figure 11 it can be seen that the effect of handling loads on the stress-strain properties of the laminate is as follows:

(a) The laminate with the amorphous phosphate coating had a higher tensile strength than the control laminate and the Young's modulus was 2.81×10^6 psi. The overall results, however, are comparable to the control properties.

(b) The samples taken from the full-scale backup balloon showed a considerable drop in Young's modulus to 0.60×10^6 psi. This drop was caused by the cracked condition of the aluminum foil. The cracks in the foil contributed to the higher than control elongation at the lowest testing speed. Otherwise, there is little change relative to the control values.

(c) The test results of the samples taken from the 30-inch test balloon are similar to those obtained with samples of the backup balloon except that Young's modulus dropped to 1.23×10^6 psi.

(d) The seams taken from the 30-inch balloon have about the same properties as the skin (Young's modulus was 1.18×10^6 psi) except for the high elongation at the highest testing speed. The elongation is possibly due to the extra layer of adhesive and tape in the seams. In general, the handling and fabrication loads have little effect on the tensile strength of the Echo II laminate, decrease the Young's modulus, and increase the elongation.

Flexural stiffness.- Samples of the Echo II laminate were taken from the 30-inch test balloon to determine the effect of handling loads on the flexural stiffness. The test specimens, in their original condition, were wrinkled in such a way that the stiffness values would be influenced. Therefore, each specimen was loaded to a certain stress and then the stiffness was measured. The pretest stresses were 3,000, 5,000, 7,000, and 10,000 psi. The test results are listed in table IX and are shown in figure 12 which includes the stiffness curve of the control laminate from figure 10. To take into account any residual stresses which might have been locked into the laminate, the stiffness tests were performed with both the outside and the inside layers of the laminate in tension. During the stiffness test the top layer of the laminate is in tension; the bottom layer, in compression.

The stiffness of the sample of laminate taken from the 30-inch balloon was higher than the stiffness of the control laminate. The curve obtained from the tests with the outside layer in tension is virtually linear with stress. At the lower stresses the stiffness is considerably higher than the control stiffness, but for a prestress of 10,000 psi the stiffnesses are about equal. The curve for the inside layer in tension has a shape that is similar to but is higher than the control curve. A part of the increased stiffness may have been caused by small wrinkles in the transverse direction which were not pulled out when the laminate strips were loaded. It would appear then that the inflation testing of a 30-inch test balloon tends to increase the stiffness of the laminate. Considering the small size and the greater care which is possible during fabrication, it is questionable whether the flexural stiffness results obtained with the 30-inch balloon would apply to the full-scale Echo II satellite.

CONCLUSIONS

The mechanical properties of the Echo II laminate have been determined by means of stress-strain tests, stress relaxation tests, and flexural stiffness tests. The following conclusions are made on the basis of these tests:

1. The tensile strength of the laminate ranges from 13,000 to 15,000 psi based on the total thickness area. The Young's modulus is about 4×10^6 psi, and the elongation at break is 8 to 10 percent. The behavior of the poly[ethylene terephthalate] film in the laminate strongly influences the behavior of the laminate with regard to strength and elongation. However, the aluminum foil contributes substantially to the Young's modulus and the flexural stiffness of the laminate. The flexural stiffness of 1/2-inch-wide strips of the laminate is 2.92×10^{-4} lb-in. The stiffness tends to decrease when the laminate is prestressed above 4,000 psi.

2. The load-deformation curves generated by the strip chart recorder on the testing machine are representative of the overall stress-strain behavior of the laminate. Samples of the laminate which have been prestressed have a higher Young's modulus than samples which have not been prestressed.

3. The stress relaxation tests indicate that the laminate has a lower rate of stress decay in a lower stress range (up to 5,000 psi) than it does in a higher range (6,000 to 10,000 psi). The stress-strain tests conducted after stress relaxation had taken place, together with the tests in which the laminate was prestressed, indicate that prestressing the laminate brings about a change in Young's modulus which is stress-dependent and not time-dependent.

4. The handling and fabrication loads have little effect of the tensile strength of the laminate. These loads, however, do tend to decrease the Young's modulus and increase the elongation. The successive inflation of a 30-inch test balloon increases the stiffness of the laminate over that of the control. If the laminate is stressed to 10,000 lb/sq in. before the stiffness is measured, then the balloon skin and the control have a stiffness of about 1×10^{-4} lb-in.^{2}.

Langley Research Center,
National Aeronautics and Space Administration,
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TABLE I.- TENSILE PROPERTIES OF 1/2-INCH BY 5-INCH SPECIMENS OF THE ECHO II LAMINATE

Strain rate, in./in./min	Tensile strength, psi	Elongation, percent	Strain rate, in./in./min	Tensile strength, psi	Elongation, percent
0.02	13,800	7.8	0.4	13,300	7.6
.02	13,700	6.2	.4	13,500	7.5
.02	12,000	2.7	.4	13,500	9.0
.02	12,400	3.0	.4	13,600	8.5
.02	12,700	8.3			
			1	15,200	14.0
.04	12,700	5.3	1	14,900	11.2
.04	12,700	4.6	1	14,900	12.0
.04	12,900	7.7	1	15,100	14.0
.04	13,000	7.5	1	15,200	14.0
.04	13,000	8.5			
			2	14,300	5.2
.1	14,600	9.5	2	15,000	9.2
.1	14,300	9.0	2	15,000	12.0
.1	14,300	9.0	2	15,500	18.0
.1	14,800	13.5	2	15,300	12.0
.1	14,400	10.0			
			4	14,000	8.0
.2	14,300	9.0	4	14,100	8.0
.2	14,400	8.6	4	14,300	8.0
.2	14,600	9.8	4	14,300	8.4
.2	14,700	10.8			
.2	14,700	11.6			

TABLE II.- TENSILE PROPERTIES OF 1/2-INCH BY 5-INCH SPECIMENS OF 0.00035-INCH-THICK POLY[ETHYLENE TEREPHTHALATE] FILM

Strain rate, in./in./min	Tensile strength, psi	Elongation, percent	Strain rate, in./in./min	Tensile strength, psi	Elongation, percent
0.02	29,400	142	0.4	29,200	118
.02	24,200	91	.4	27,500	109
.02	26,800	121	.4	27,500	115
.02	21,200	79	.4	27,300	114
.02	19.500	80	.4	21,100	65
.04	20,000	45	1	27,700	129
.04	20,000	47	1	30,600	149
.04	20,100	57	1	31,100	148
.04	21,100	140	1	24,300	93
			1	24,500	95
.1	22,700	94			
.1	23,000	81	2	22,200	68
.1	24,500	93	2	23,800	77
.1	26,900	115	2	32,200	132
.1	24,500	94	2	27,800	101
			2	20,000	34
.2	23,900	102			
.2	28,400	138	4	32,800	136
.2	26,300	130	4	28,900	116
.2	25,200	121	4	30,000	130
.2	27,200	116	4	20,200	54
			4	27,000	119

TABLE III.- TENSILE PROPERTIES OF 1/2-INCH BY 5-INCH SPECIMENS OF 0.0002-INCH-THICK 1080 ALUMINUM FOIL

Strain rate, in./in./min	Tensile strength, psi	Elongation, percent	Strain rate, in./in./min	Tensile strength, psi	Elongation, percent
0.02	8,100	1.1	0.4	8,100	0.9
.02	7,700	1.0	.4	8,700	1.4
.02	8,470	1.2	.4	8,500	1.1
.02	7,630	1.0	.4	8,200	1.2
.02	8,180	.9	.4	7,900	.8
.04	7,900	.8	1	7,800	.9
.04	8,100	1.0	1	8,500	1.3
.04	8,000	1.0	1	7,200	.8
.04	8,040	1.0	1	8,200	1.1
.04	8,550	1.4	1	8,200	1.1
.1	8,900	1.3	2	8,100	1.0
.1	8,300	1.2	2	7,800	1.0
.1	8,000	.9	2	8,000	1.0
.1	8,400	1.1	2	7,900	1.0
.1	8,450	1.0	2	7,800	1.0
.2	8,100	1.0	4	8,500	1.2
.2	8,800	1.0	4	7,500	1.4
.2	8,100	1.0	4	8,200	1.6
.2	8,600	1.0	4	7,500	.8
.2	8,600	1.0	4	7,000	1.2

TABLE IV.- TENSILE PROPERTIES OF 1/2-INCH BY 5-INCH SPECIMENS OF TWO-PLY, 0.0002-INCH-THICK, 1080 ALUMINUM FOIL LAMINATE

Strain rate, in./in./min	Tensile strength, psi	Elongation, percent
0.04	9,700	1.8
.04	10,100	2.2
.04	9,800	1.8
.04	9,600	1.4
.4	10,200	1.8
.4	10,200	1.9
.4	10,400	2.2
.4	10,700	2.5
4	10,000	1.2
4	10,000	1.6
4	10,000	1.6
4	10,000	1.6

TABLE V.- TENSILE STRESS RELAXATION AND POST-TEST TENSILE PROPERTIES

OF 1/2- BY 5-INCH SPECIMEN OF ECHO II LAMINATE

Initial stress, psi	Stress at a time of -													Post-test tensile properties		
	0.1, min	0.2, min	0.5, min	1, min	2, min	5, min	10, min	20, min	50, min	100, min	200, min	500, min	1,000, min	Tensile strength, psi	Young's modulus, psi	Elongation, percent
1,000	965	960	940	920	880	855	835	815	780	765	745	725	690	------	----------	----
1,140	1,040	1,025	1,000	980	965	935	890	880	860	840	820	810	775	13,700	2.21×10^6	25.3
1,175	1,090	1,075	1,060	1,040	1,030	1,005	995	965	925	915	915	930	935	13,600	2.11	11.5
1,800	1,700	1,680	1,660	-----	1,600	1,570	1,560	1,550	1,540	1,550	1,500	1,560	1,680	15,900	3.97	36.1
1,980	1,830	1,810	1,760	1,720	1,690	1,640	1,580	1,540	1,470	1,440	1,390	1,350	1,270	15,300	2.13	31.3
3,000	2,770	2,730	2,670	2,610	2,550	2,470	2,410	2,350	2,250	2,190	2,130	2,070	1,990	14,700	3.00	25.5
3,090	2,880	2,850	2,790	2,740	2,700	2,620	2,580	2,530	2,450	2,410	2,360	2,320	2,170	14,500	3.89	16.2
4,050	3,830	3,790	3,720	3,660	3,610	3,520	3,470	3,390	3,300	3,270	3,190	3,160	3,060	13,900	4.18	12.1
	3,800	3,740	3,680	3,600	3,530	3,430	3,390	3,300	3,180	3,090	3,020	-----	2,900	9,500	3.70	1.9
5,000	4,690	4,630	4,540	4,460	4,370	4,270	4,200	4,100	3,980	3,880	3,770	3,700	-----	15,700	4.09	34.1
	4,680	4,620	4,540	4,470	4,400	4,490	4,230	4,140	4,030	3,940	3,850	3,720	3,670	15,700	----------	38.1
6,000	5,960	5,620	5,540	5,470	5,380	5,270	5,180	5,090	4,960	4,850	4,740	4,620	4,530	13,100	4.53	8.4
	5,640	5,570	5,550	5,400	5,310	5,180	5,080	4,960	4,820	4,810	4,740	4,620	4,480	------	----------	----
8,000	7,520	7,420	7,260	7,120	6,990	6,830	6,710	6,580	6,420	6,280	6,140	6,000	5,910	8,400	3.85	.9
	7,610	7,520	7,390	7,290	7,170	7,010	6,820	6,720	6,550	6,420	6,280	6,120	6,020	11,100	4.16	1.9
10,000	9,500	9,390	9,210	9,050	8,880	8,680	8,530	8,360	8,100	7,890	7,600	7,400	7,170	11,900	4.17	2.1
	9,520	9,410	9,240	9,090	8,900	8,700	8,510	8,300	8,010	7,820	7,640	7,380	7,180	12,800	3.14	4.0

TABLE VI.- FLEXURAL STIFFNESS OF 1/2-INCH-WIDE STRIPS OF ECHO II LAMINATE, 0.00035-INCH-THICK POLY [ETHYLENE TEREPHTHALATE] FILM, AND 0.0002-INCH-THICK 1080 ALUMINUM FOIL

Deflection angle, deg	Length of overhang, in.	Flexural stiffness, lb-in.^{2}
	Echo II laminate	
11	2.25	2.04×10^{-4}
11	2.34	2.29
11	2.47	2.69
12	2.73	3.32
12	2.79	3.58
12	2.80	3.62
13	2.88	3.63
13	3.27	5.32
14	2.49	2.16
14	2.92	3.49
14	3.08	4.09
15	2.11	1.26
15	2.75	2.73
15	2.82	2.87
16	2.82	2.80
16	2.86	2.86
16	2.96	3.17
16	3.05	3.47
16	3.05	3.47
17	2.68	2.21
17	2.98	3.03
18	2.83	2.43
18	3.00	2.90
18	3.10	3.21
19	2.94	2.57
19	3.38	3.91
22	2.61	1.53
23	3.67	4.02
25	3.45	3.04
25	3.60	3.46
26	3.79	3.83
27	3.67	3.31
27	3.72	3.39
27	3.73	3.48
28.5	3.73	3.25
29	3.70	3.09
29	3.73	3.16
29	3.99	3.87

TABLE VI.- FLEXURAL STIFFNESS OF 1/2-INCH-WIDE STRIPS OF ECHO II LAMINATE, 0.00035-INCH-THICK POLY[ETHYLENE TEREPHTHALATE] FILM, AND 0.0002-INCH-THICK 1080 ALUMINUM FOIL - Continued

Deflection angle, deg	Length of overhang, in.	Flexural stiffness, lb-in.^{2}
Echo II laminate - Concluded		
30	3.70	2.95×10^{-4}
31	3.83	3.13
31	4.35	4.58
32	3.68	2.65
33	3.35	1.91
34	3.52	2.12
34	3.84	2.75
34	3.89	2.85
36	3.17	1.41
36	3.59	2.02
39	3.90	2.32
40	4.48	3.36
42	4.00	2.20
42	4.86	3.92
45	4.34	2.47
45	4.51	2.75
45	4.59	2.90
45	4.65	3.02
45	4.68	3.07
45	4.72	3.15
46	4.56	2.74
47	4.66	2.79
47	4.67	2.81
47	4.69	2.85
47	4.83	3.12
47.5	3.98	1.71
48	4.08	1.80
48	4.35	2.18
49	4.44	2.22
49	4.75	2.73
50	4.49	2.21
50	4.94	2.81

TABLE VI.- FLEXURAL STIFFNESS OF 1/2-INCH-WIDE STRIPS OF ECHO II LAMINATE, 0.00035-INCH-THICK POLY[ETHYLENE TEREPHTHALATE] FILM, AND 0.0002-INCH-THICK 1080 ALUMINUM FOIL - Concluded

Deflection angle, deg	Length of overhang, in.	Flexural stiffness, lb-in.^{2}
Poly[ethylene terephthalate] film		
12	0.52	7.11×10^{-7}
12	.55	8.42
13	.55	7.77
19	.87	20.53
28	.75	8.30
30	.94	14.86
34	.90	10.85
35	.87	9.49
39	.92	9.36
42	.96	9.28
42	1.09	13.58
51	1.27	14.66
Aluminum foil		
18	1.11	4.77×10^{-6}
18	1.13	4.44
22	1.16	4.55
22	1.23	5.41
25	1.30	5.47
27	1.07	2.77
27	1.24	4.31
27	1.68	10.73
28	1.37	5.57
34	1.28	3.43
39	1.49	4.35
40	1.52	4.43
40.5	1.48	4.00
41	1.58	4.78
41	1.94	8.84
42	1.45	3.54
44	1.64	4.64
44	1.65	4.72
45	1.55	3.77
51	1.81	4.67
54	1.72	3.53
55	1.83	4.10
55.5	1.91	4.56

TABLE VII.- THE EFFECT OF APPLIED AND RELEASED TENSILE STRESS ON THE FLEXURAL STIFFNESS OF 1/2-INCH-WIDE STRIPS OF ECHO II LAMINATE

Stress, psi	Deflection angle, deg	Length of overhang, in.	Flexural stiffness, lb-in.^{2}
0	----	----	[a]2.92×10^{-4}
3,000	23.5	3.30	2.87
3,000	29.5	3.35	2.24
3,000	10	2.66	[b]5.08
3,000	41	4.00	2.28
4,000	22	3.45	3.54
4,000	31	3.40	2.18
4,000	12.5	2.90	[b]5.38
4,000	34	3.76	2.57
4,000	14	3.02	[b]3.87
5,000	35.5	4.02	2.95
5,000	15.5	3.29	[b]4.49
5,000	37.5	3.67	2.36
5,000	21.5	2.80	[b]1.94
5,000	39	3.37	1.50
5,000	22.5	2.74	[b]1.73
5,000	11	2.00	[b]1.43
5,000	48	4.00	1.66
6,000	39	3.93	2.37
6,000	41.5	3.77	1.86
6,000	18.5	2.82	[b]2.35
6,000	49	3.85	2.65
6,000	36.5	3.14	[b]1.35
6,000	11.5	2.13	[b]1.66
6,000	51	4.00	1.49
8,000	52	4.00	1.42
8,000	56.5	4.02	1.21
8,000	28.5	3.01	[b]1.71
8,000	12.5	2.32	[b]1.97
8,000	56.5	3.96	1.16
8,000	34.5	3.07	[b]1.37
8,000	18.5	2.24	[b]1.17
8,000	58.5	4.15	2.43
8,000	28.5	3.19	[b]2.03
10,000	53	4.00	1.41
10,000	55.5	3.44	.79
10,000	40.5	2.79	[b].79
10,000	16	2.08	[b]1.10
10,000	58	3.53	.77
10,000	38.5	2.78	[b].86
10,000	13	2.04	[b]1.29
10,000	58.5	3.69	.86
10,000	34.5	2.78	[b]1.01
10,000	12.5	2.04	[b]1.35

[a]Average of 70 tests (see table VI).
[b]Additional tests made on same strip.

TABLE VIII.- THE EFFECT OF FABRICATION AND HANDLING LOADS ON THE TENSILE PROPERTIES OF 1/2-INCH BY 5-INCH SPECIMENS OF THE ECHO II LAMINATE

Strain rate, in./in./min	Tensile strength, psi	Elongation, percent
Laminate with an amorphous phosphate coating		
0.04	13,900	7.7
.04	14,100	8.8
.04	14,200	9.0
.04	13,700	7.1
.04	14,100	9.5
.4	14,200	7.6
.4	14,200	9.1
.4	13,800	7.1
.4	13,800	8.0
4	14,500	8.4
4	14,700	11.2
4	14,700	8.8
4	14,400	10.4
Laminate from a full-scale satellite		
0.04	12,900	40.0
.04	13,100	10.0
.04	13,200	11.6
.4	13,600	9.2
.4	12,800	5.2
.4	13,400	9.6
4	14,300	10.4
4	14,300	11.2
Laminate from a 30-inch balloon		
0.04	12,200	17.2
.04	12,200	15.0
.04	15,500	15.8
.4	12,900	8.4
.4	12,500	12.0
.4	12,900	8.0
4	13,300	13.6
4	13,300	12.0
4	13,500	10.4
Seams from a 30-inch balloon		
0.04	13,100	6.8
.04	10,900	4.0
.04	13,500	8.6
.4	13,900	10.0
.4	13,900	9.0
.4	13,700	16.5
.4	13,800	9.3
4	15,100	17.2
4	14,500	20.8

TABLE IX.- THE EFFECT OF APPLIED AND RELEASED TENSILE STRESS ON THE FLEXURAL STIFFNESS OF ECHO II LAMINATE TAKEN FROM A 30-INCH TEST BALLOON

Stress, psi	Deflection angle, deg	Length of overhang, in.	Flexural stiffness, lb-in.^{2}
Outside layer in tension			
3,000	19	3.90	6.00×10^{-4}
3,000	23	3.96	5.09
3,000	11	2.85	[a]4.14
3,000	24	3.98	4.89
5,000	22	3.76	4.58
5,000	29	4.03	3.97
5,000	41	4.30	2.85
5,000	17	3.05	[a]3.24
7,000	26	3.85	4.00
7,000	18.5	2.88	[a]2.50
7,000	33	4.02	3.29
7,000	17	3.05	[a]3.36
7,000	10	2.16	[a]2.01
7,000	43	4.08	2.22
7,000	25	3.00	[a]1.99
7,000	10	1.83	[a]1.22
10,000	36	2.61	.79
10,000	16	1.69	[a].59
10,000	43	3.16	1.03
10,000	12	2.05	[a]1.44
10,000	44	3.08	.86
10,000	12	1.88	[a]1.09
Inside layer in tension			
3,000	28	4.19	2.54×10^{-4}
3,000	14.5	3.03	[a]3.77
3,000	29	4.00	3.88
3,000	16	2.97	[a]3.20
3,000	37	4.17	3.11
3,000	20.5	3.15	[a]2.92
5,000	17	3.20	3.73
5,000	29	4.11	4.23
5,000	34	4.08	3.29
5,000	10	2.97	[a]7.08
5,000	37	4.25	3.28
5,000	18	3.09	[a]3.18
7,000	14	2.92	3.49
7,000	27	3.96	4.16
7,000	18.5	3.01	[a]2.94
7,000	10	1.92	[a]1.41
7,000	28	3.85	3.66
7,000	33	4.00	3.22
7,000	10	3.04	[a]5.99
10,000	44	3.76	1.66
10,000	15	2.61	[a]2.33
10,000	50	4.35	2.01
10,000	21	3.09	[a]2.68
10,000	55	4.13	1.39
10,000	18	2.89	[a]2.60

[a]Additional tests made on same strip.

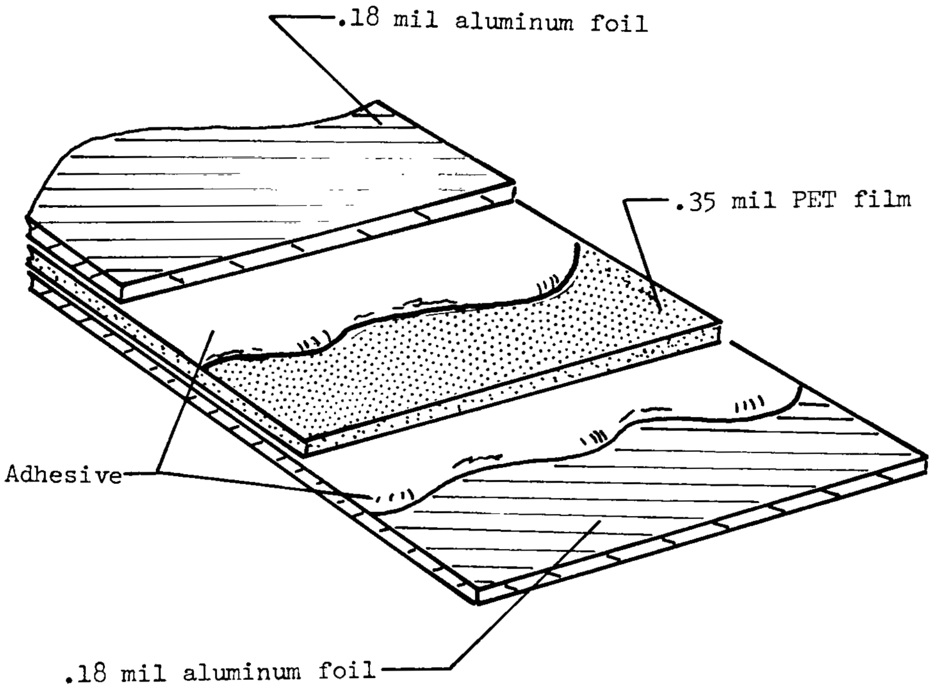
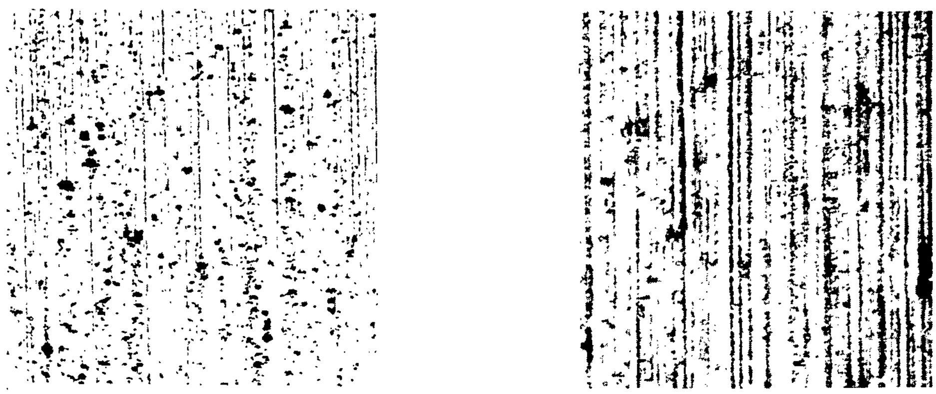
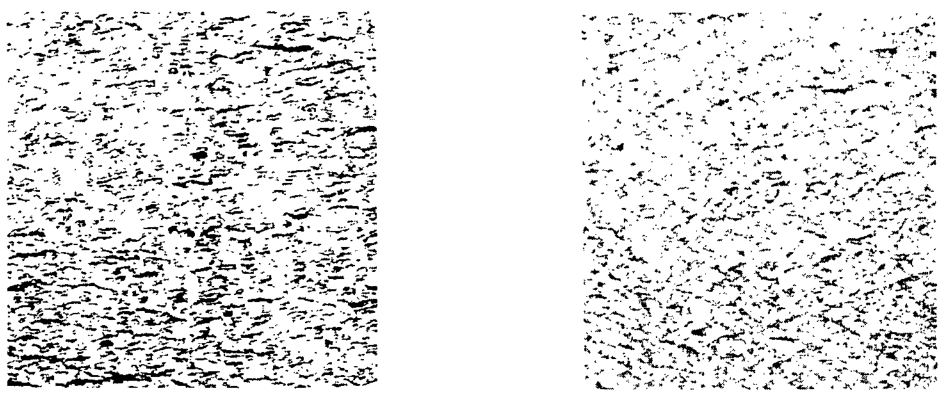


Figure 1.- Construction of the Echo II laminate.

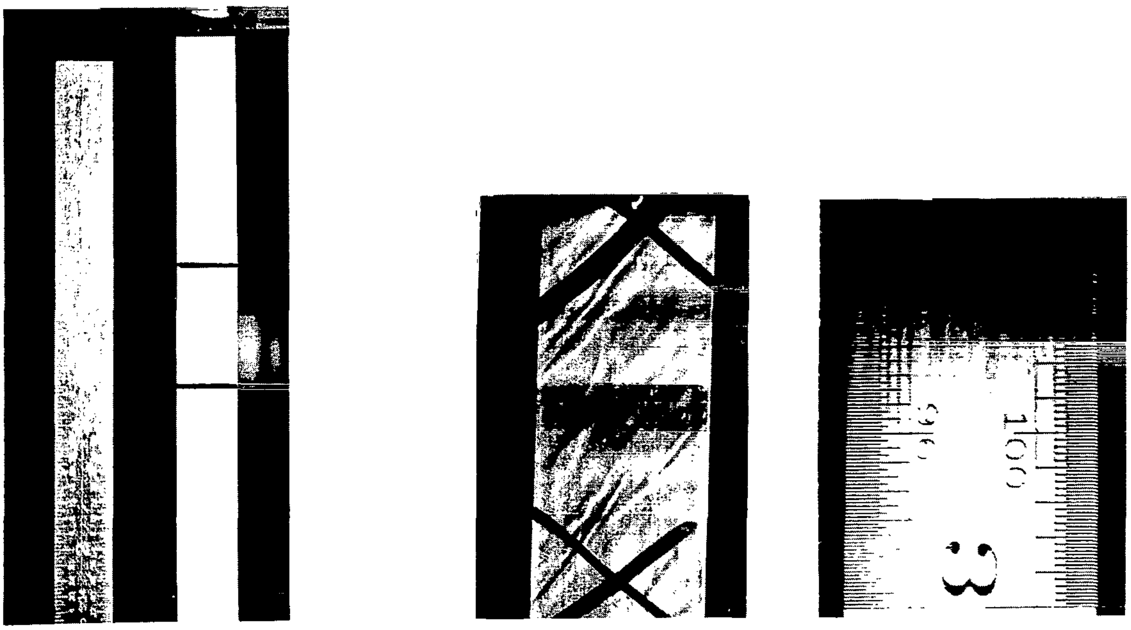


(a) Aluminum foil.



(b) Echo II laminate.

Figure 2.- Micrographs of the shiny side of 0.00018-inch 1080 aluminum foil and Echo II laminate at 100X magnification. Left micrograph made in direct light, right micrograph in oblique light.



(a) Stress-strain test.

(b) Modulus test.

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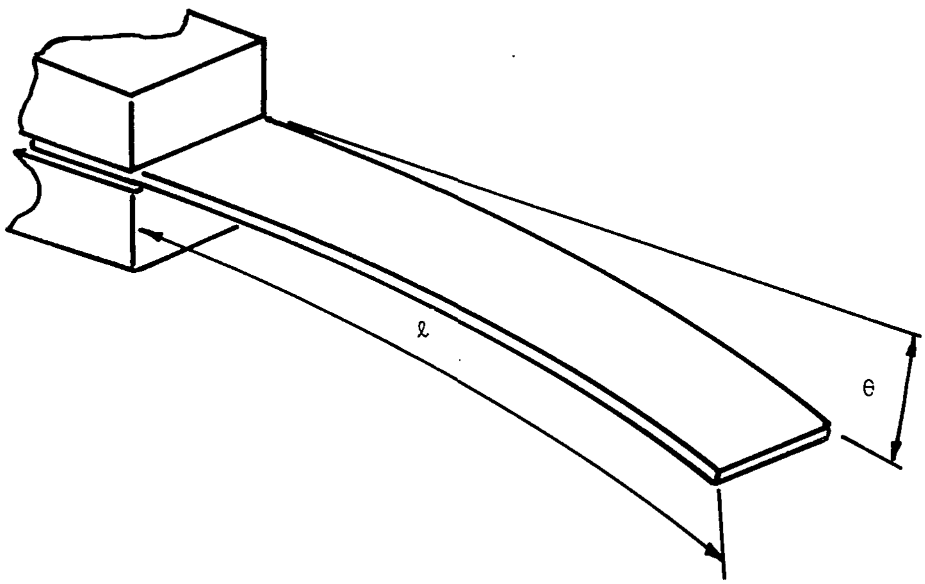
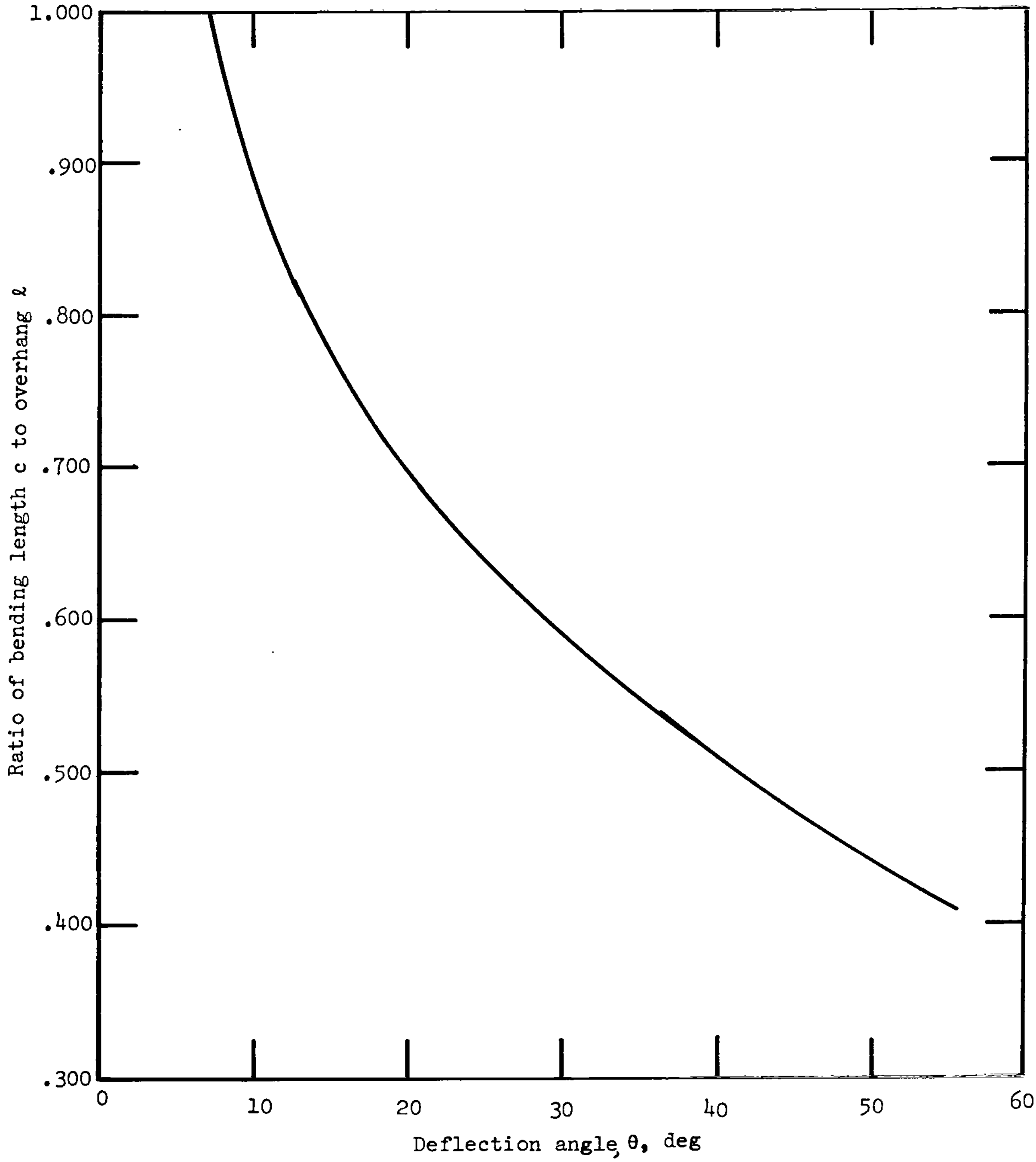
Figure 3.- Frames taken from the photographic records of the stress-strain test and the modulus tests in which the strain was measured optically. The load is applied in the vertical direction.



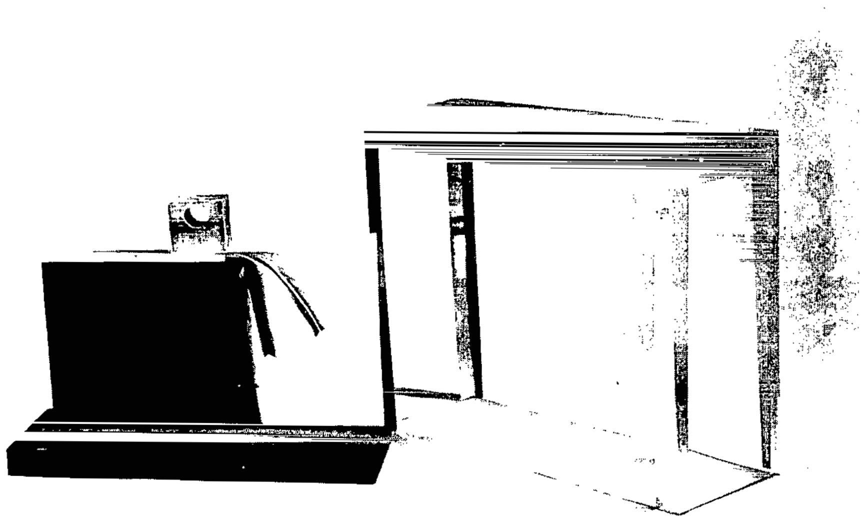
(a) Schematic diagram of the heavy elastica method of measuring stiffness.

Figure 4.- Stiffness tester employing the heavy elastica method for measuring the stiffness of the Echo II laminate.



(b) The relationship between the deflection angle θ and the ratio of c/l for a cantilever, where c is the bending length and l is the length of overhang.

Figure 4.- Continued.



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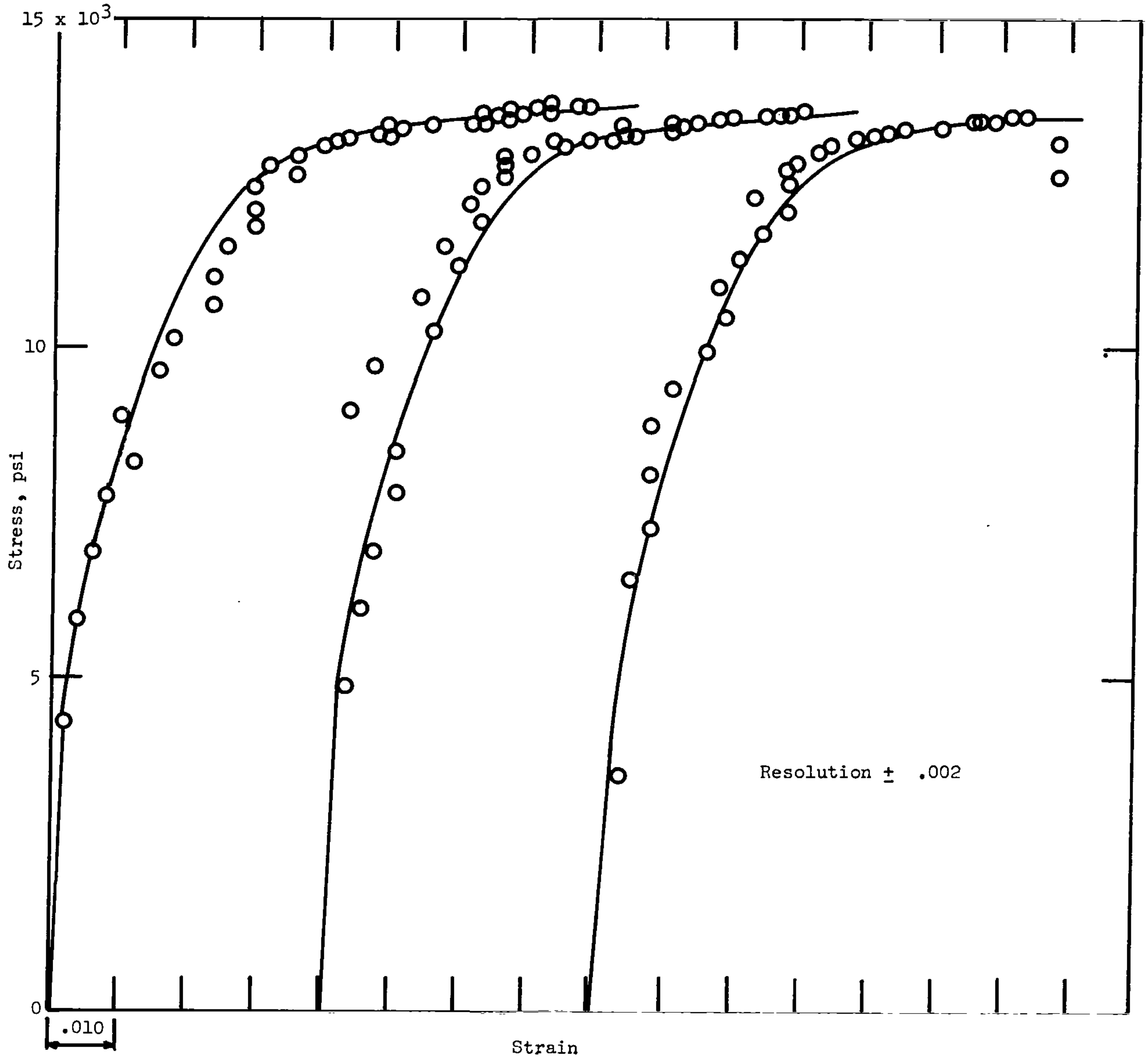
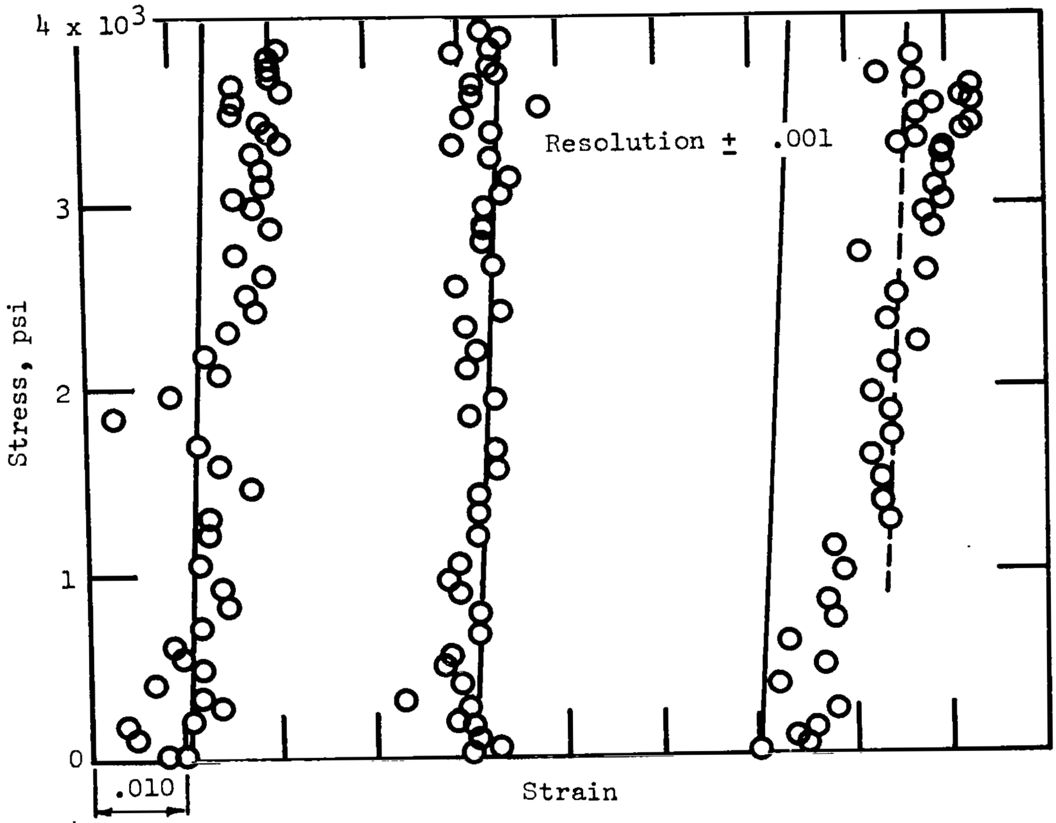
(c) Stiffness tester showing the relative stiffness of the Echo I, Echo II, and the Explorer IX laminate.

Figure 4.- Concluded.



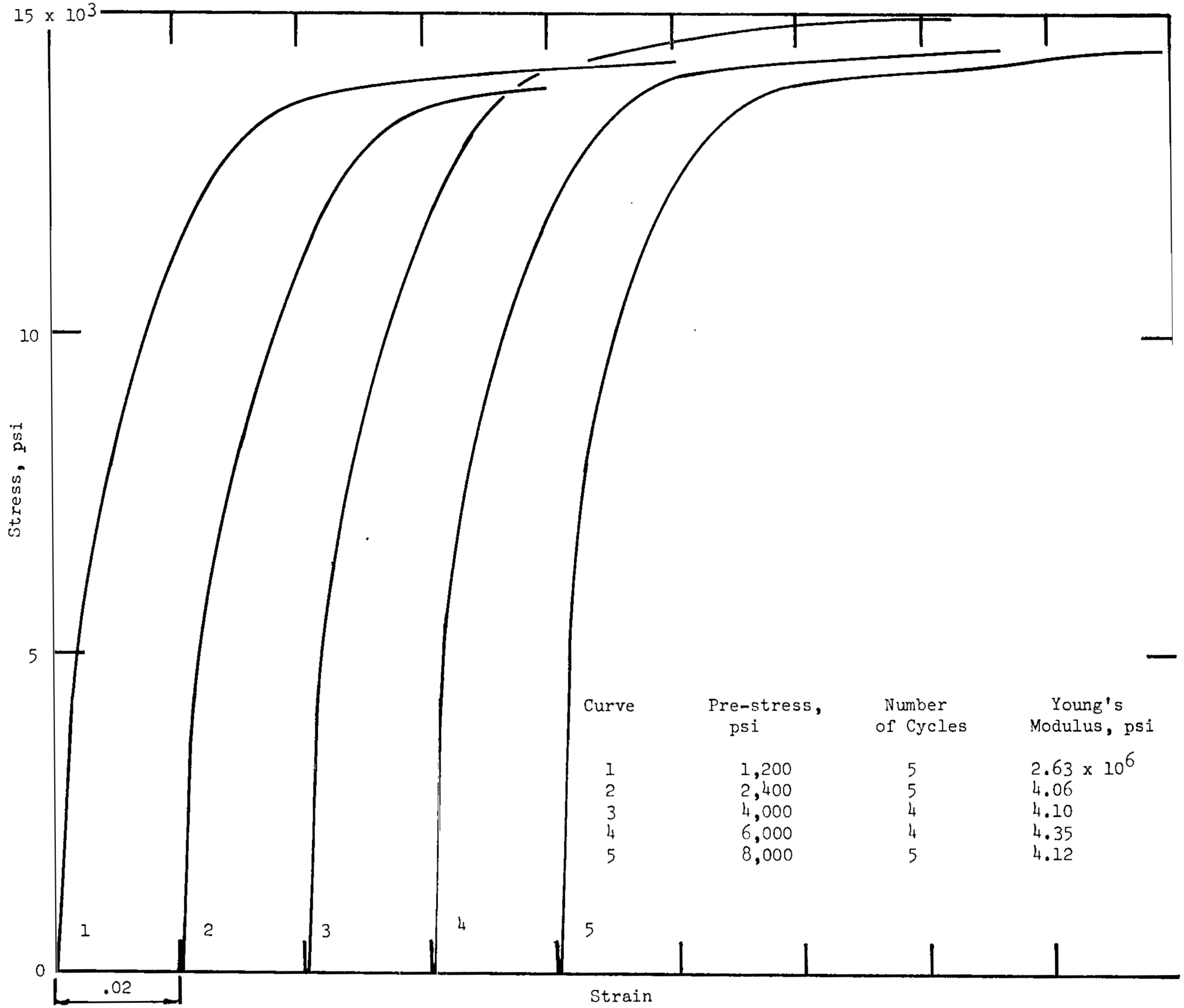
(a) Stress-strain tests.

Figure 5.- Stress-strain curves of the Echo II laminate for a strain rate of 0.04 inch per inch per minute. The solid curves were generated by the testing machine recorder and the data points were obtained by means of optical measurements. The resolution of the camera-film reader system is indicated.



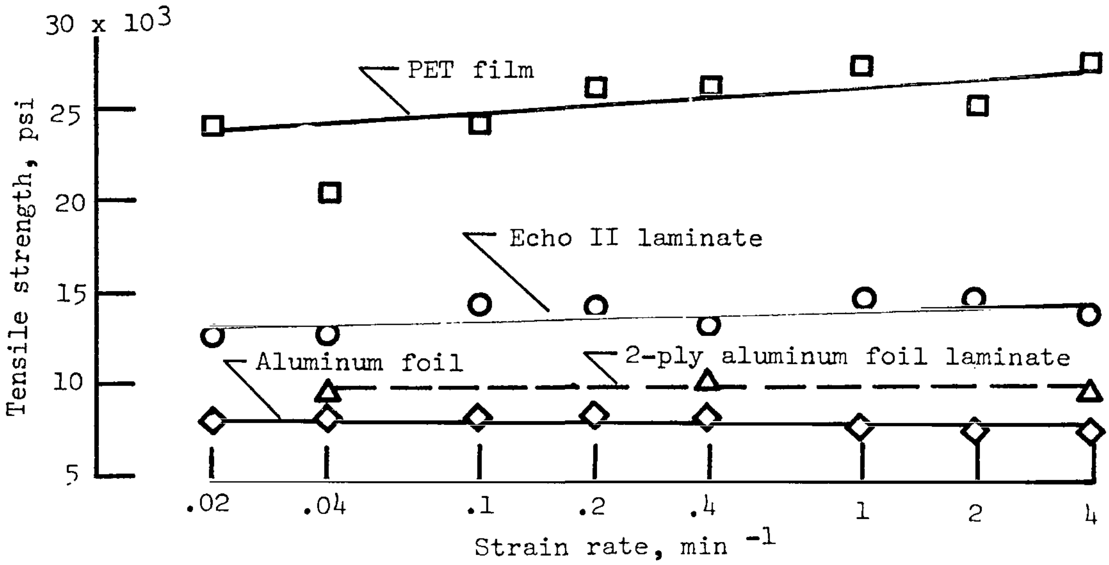
(b) Modulus tests.

Figure 5.- Concluded.

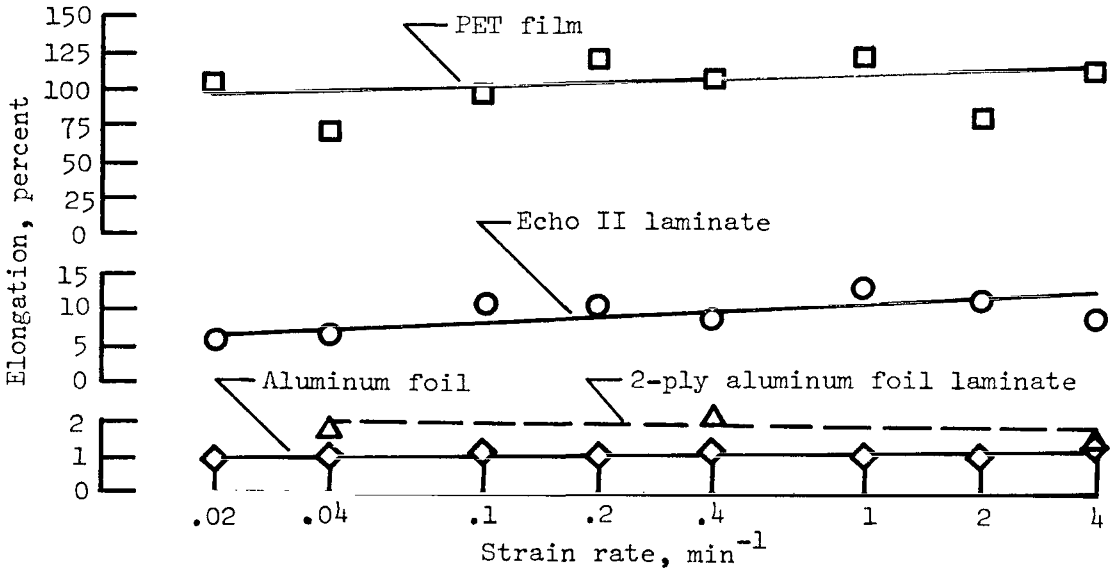


Curve	Pre-stress, psi	Number of Cycles	Young's Modulus, psi
1	1,200	5	2.63×10^6
2	2,400	5	4.06
3	4,000	4	4.10
4	6,000	4	4.35
5	8,000	5	4.12

Figure 6.- Tensile stress-strain curves of the Echo II laminate obtained at a strain rate of 0.04 inch per inch per minute after the test specimen had been loaded to the indicated stress.



(a) Tensile strength.



(b) Elongation.

Figure 7.- Tensile strength and elongation of the Echo II laminate, the PET film, and the aluminum foil for strain rates of 0.02 to 4 inches per inch per minute. The dashed curves show the mechanical properties of the two-ply 1080 aluminum-foil laminate which was tested at strain rates of 0.04, 0.4, and 4 inches per inch per minute.

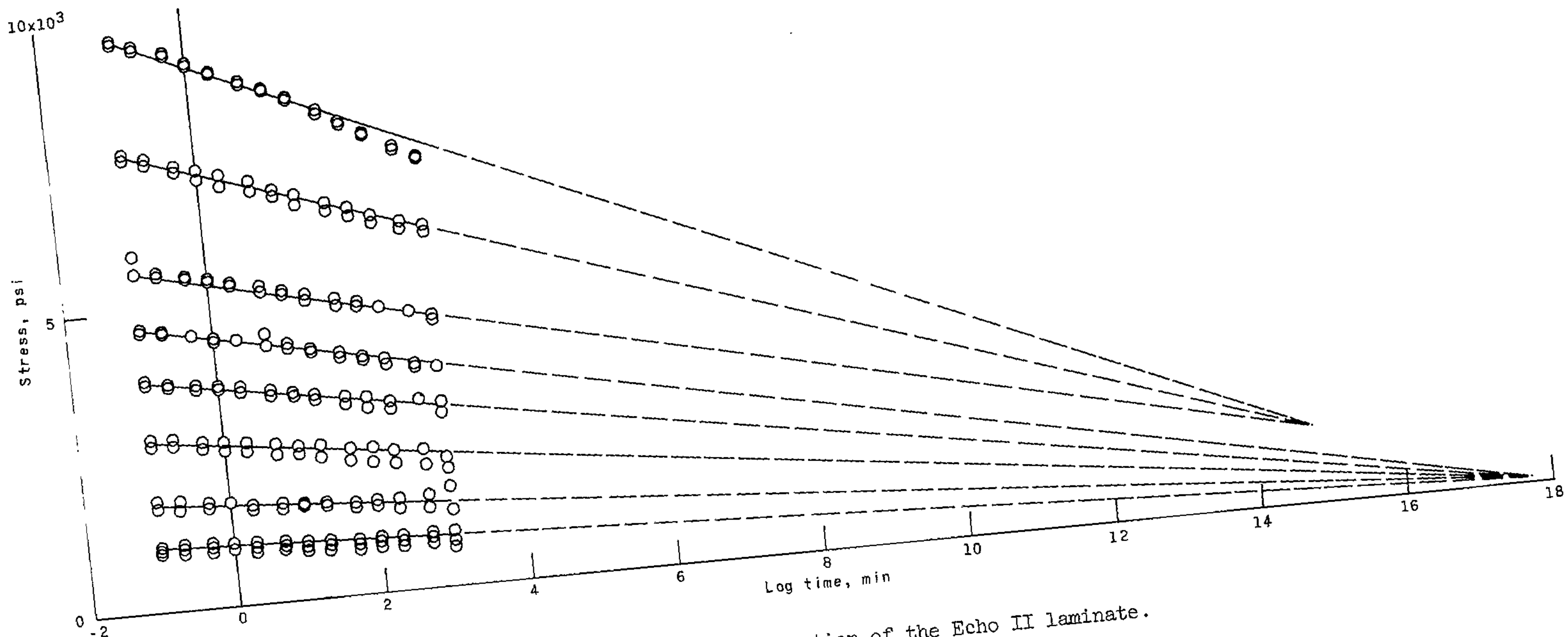


Figure 8.- Tensile stress relaxation of the Echo II laminate.

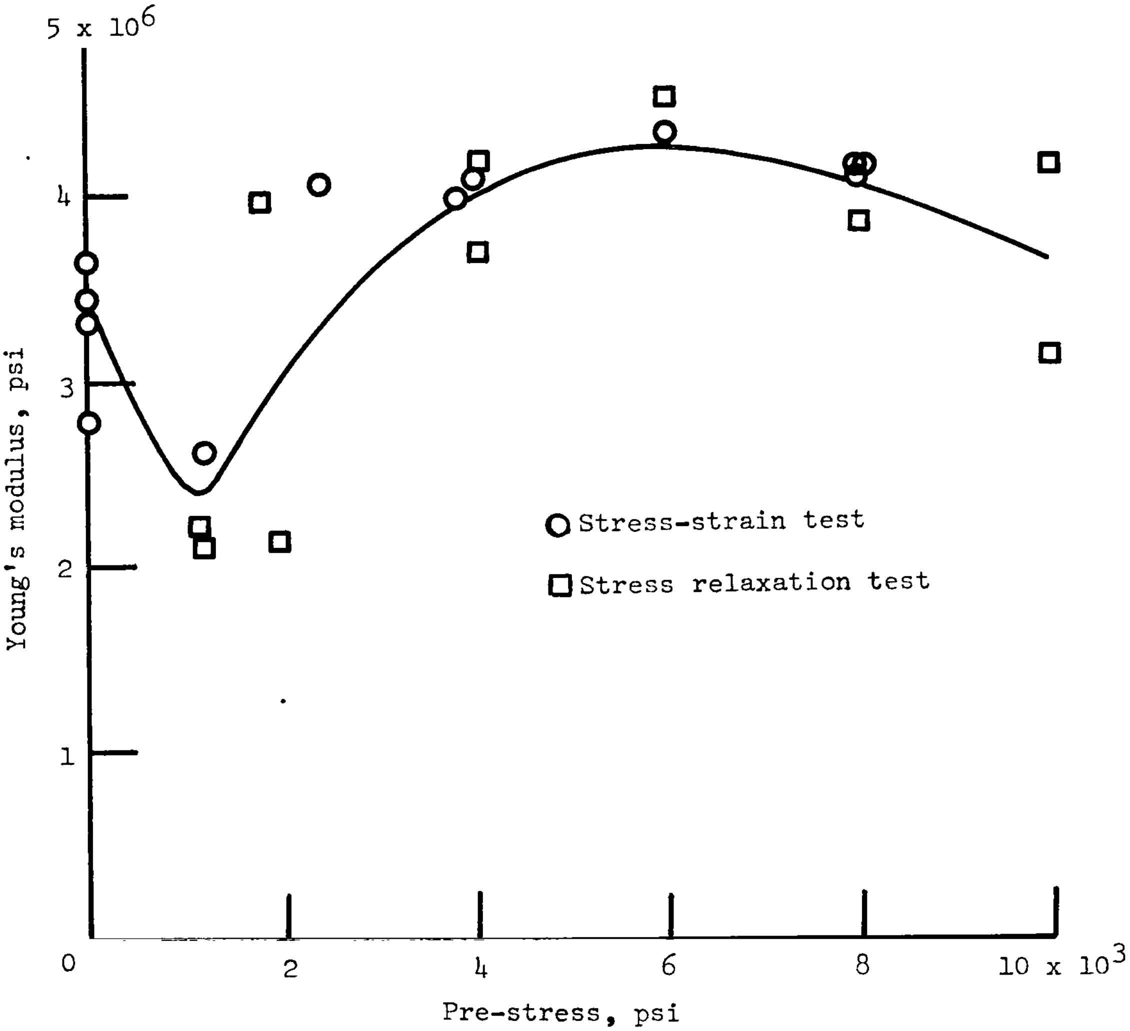


Figure 9.- The Young's modulus of the Echo II laminate as a function of the prestress applied to the laminate. All stress-strain tests were conducted at a strain rate of 0.04 inch per inch per minute.

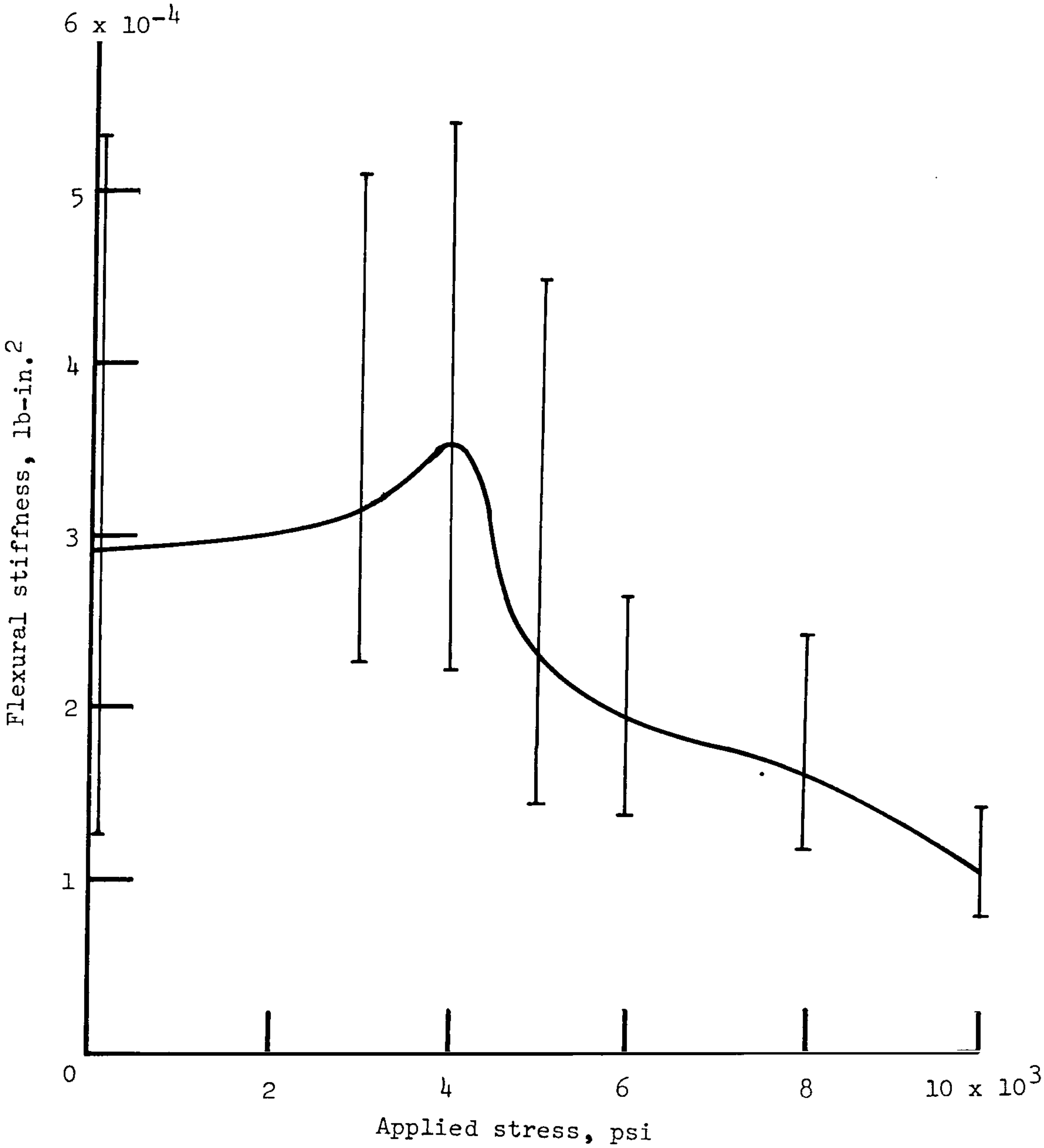
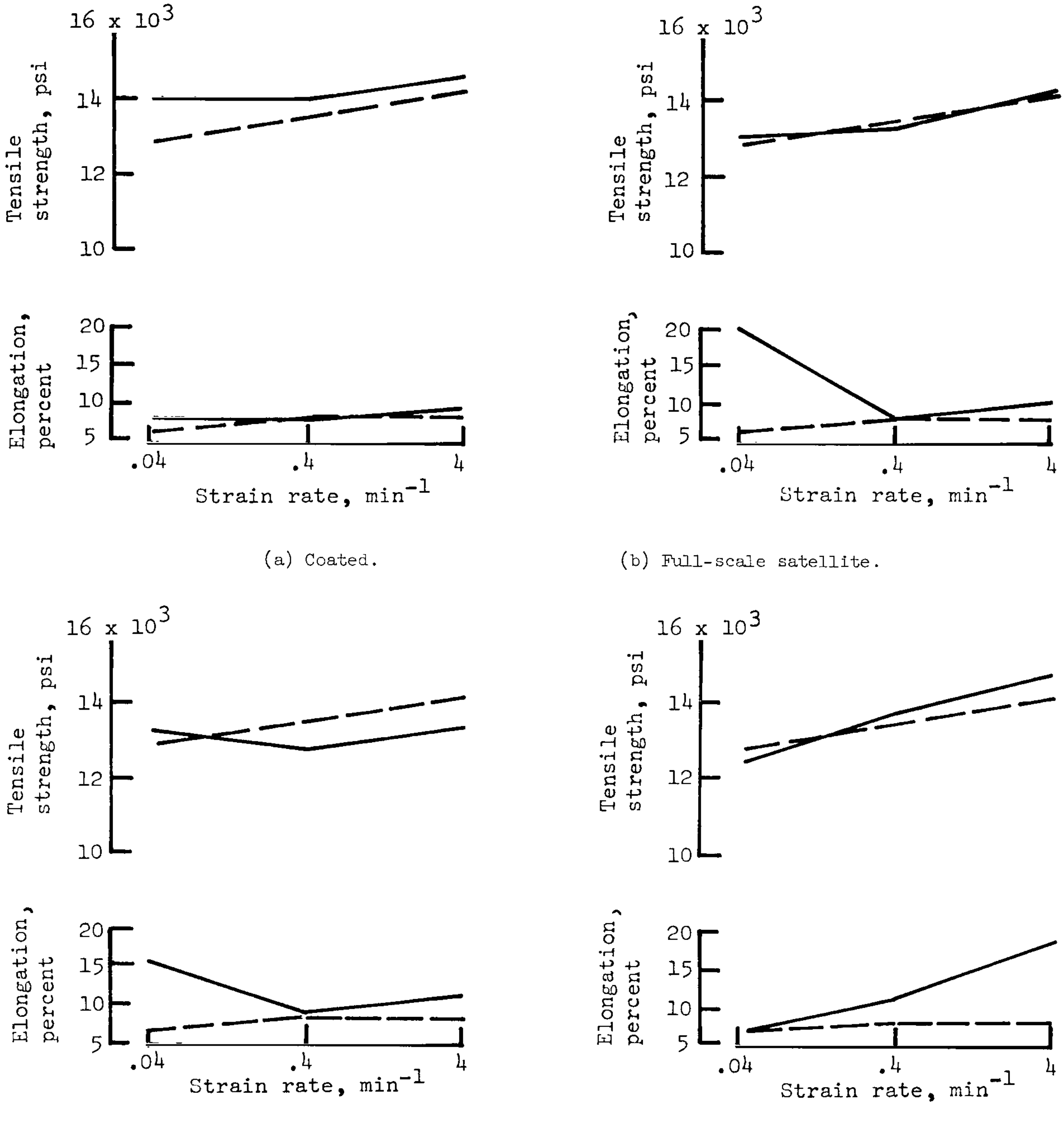


Figure 10.- Flexural stiffness of the Echo II laminate as a function of applied and released tensile stress. The error flags indicate the spread in the data.



(a) Coated.

(b) Full-scale satellite.

(c) 30-inch balloon.

(d) 30-inch balloon seams.

Figure 11.- The effect of fabrication and handling loads on the tensile properties of the Echo II laminate. The properties of the laminate which had not been subjected to handling loads are shown by the dashed curves. The dashed curves are taken from figure 7.

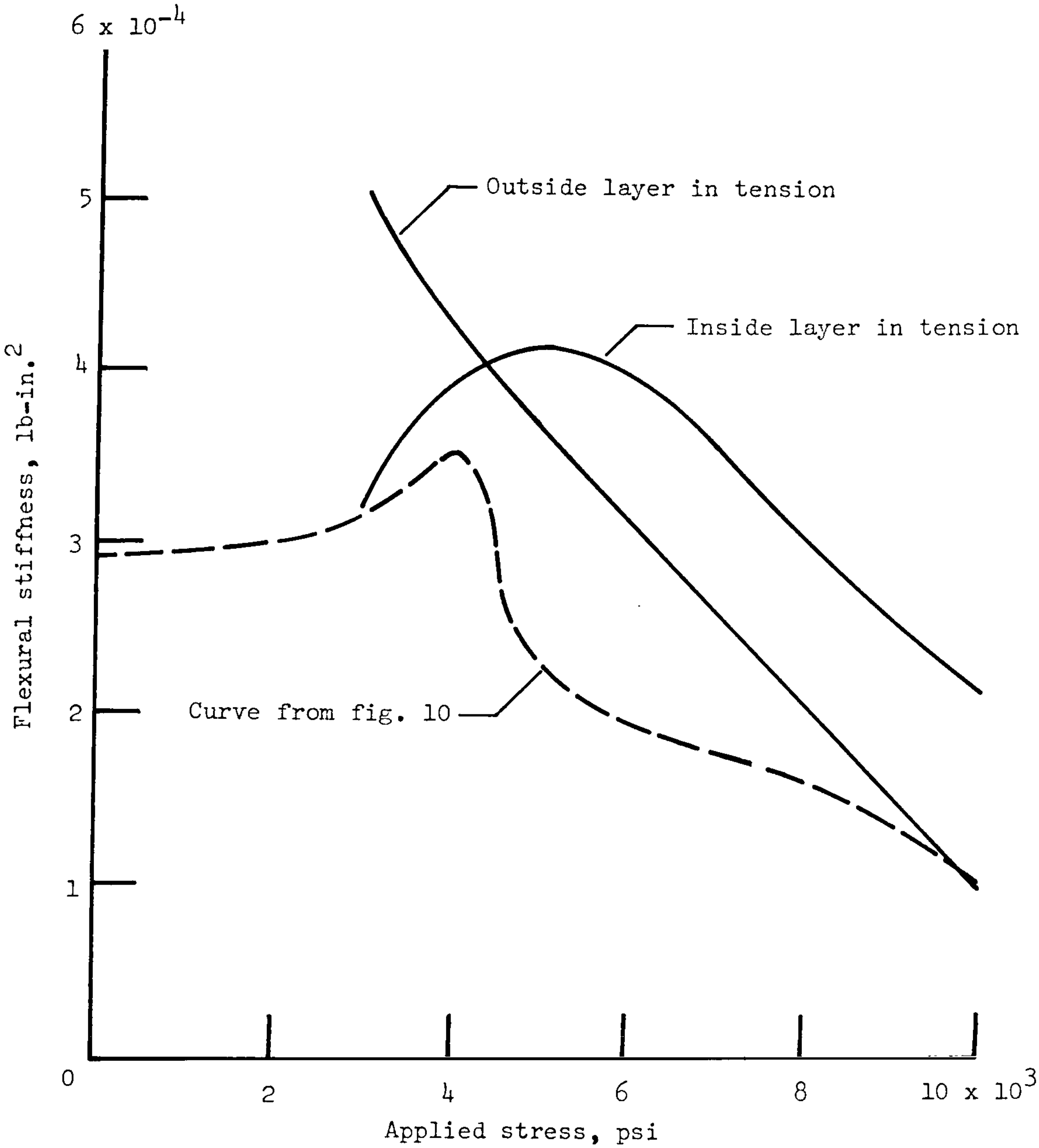


Figure 12.- The effect of applied and released tensile stress on the flexural stiffness of the Echo II laminate which was taken from a 30-inch test balloon. The curve from figure 10 is shown for comparison.

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